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Design and Fabrication of Electrostatic Actuators with Corrugated Membranes for MEMS Deformable Mirror in Space

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ABSTRACT

A novel Microelectromechanical Systems (MEMS) deformable mirror (DM) technology for large, light weight, segmented space telescopes is being proposed. This technology is reported to provide an unprecedented imaging capability in a visible and near infrared spectral range. The MEMS-DM proposed in this paper consists of a continuous membrane mirror supported by electrostatic actuators with a pixel-to-pixel spacing as small as 200 μm. An array of 4x4 electrostatic actuators for the DM has been successfully fabricated by a new membrane transfer technique. The fabricated actuator membrane has been characterized by using an optical surface profiler. The actuator shows a vertical deflection of 0.37 μm at 55 V. This device can also address requirements for smaller size and high resolution applications involving optical transmission through aberrating mediums such as imaging and optical communications through atmospheres, high resolution biometric retina signatures through the eye and endoscopic investigation of tissues and organs.

Keywords: deformable mirror (DM), Microelectromechanical Systems (MEMS), adaptive optics, electrostatic actuator, single crystal silicon (SCS) membrane, continuous mirror, wafer-level membrane transfer, Next Generation Space Telescope (NGST)

1. INTRODUCTION

Deformable mirrors (DMs) have been used in the auxiliary adaptive optics for precision wave front correction. We are building a MEMS-DM technology, which allows substantial reductions in cost over conventional space based instruments such as Hubble Space Telescope (HST), while improving imaging capability and system robustness to adapt to unanticipated mission conditions.

NASA and its industrial partners are formulating the design of the Next Generation Space Telescope (NGST) which, with an estimated 6-8m diameter aperture and cryogenic operation, will reveal more distant structures of the Universe, but in similar detail at infrared wavelengths. The NGST will likely consist of a segmented primary mirror, which breaks the scaling law by utilizing an articulated array of lighter weight, and thus, lower cost glass mirror segments. A small, lightweight, cryogenic DM has been identified as an enabling technology to achieving NGST science objectives. The MEMS technology is being taken to explore the development of the continuous DM technology with the ultimate application as the active optical surface of space based telescopes. This work paves the way for the development of a more sophisticated critical technology complement for large lightweight space telescopes of the future, whose demanding requirements need the investment in radically new mirror technologies today.

Currently, most DMs commercially available are macroscopic devices made with flat glass mirror plates supported by an array of electrostrictive actuators, operational over a limited temperature range and susceptible to hysteresis and creep. Because of these effects, they do not satisfy the requirements for an optical figure which should remain stable for a period of weeks as required by space-based telescope. The electrostrictive lead magnesium niobate (PMN) technology has been demonstrated with excellent surface stability for a period of weeks but is functional only near room temperature [1]. New electrostrictive materials such as strontium titanate are under development for 30 °K operation but do not operate at a room temperature, making system level testing difficult.

Micromachined designs have been developed by several research groups to improve the DM technology and offer the potential to be scalable and cost effective. Segmented mirrors [2-4] have been fabricated with individual pixel tip/tilt capability but a continuous mirror surface is required for astronomical adaptive optics applications. Micromachined continuous membrane DMs have been fabricated by Delft [5] and JPL [6] (the previous JPL design was substantially more rudimentary in approach than that described in this paper). Both have excellent surfaces but the mirror membranes have high inter-actuator coupling between individual pixels (influence function), and a more recent effort has produced a bulk micromachined DM with still unacceptably high influence function [7].

An electrostatically actuated surface micromachined DM [8] has been demonstrated to be one hundred times faster, one hundred times smaller, and consume ten thousand times less power than macroscopic DMs. This micromachined DM has a continuous mirror backed by parallel plate actuators, which is fabricated using the surface micromachining technology embodied in the Multi-User MEMS Processes (MUMPS). Restriction to the MUMPS process creates design limitations and marginal surface quality, which in turn limits the applicability of this approach.

A new design for the materials, structures and fabrication methods to meet the requirements of imaging astronomical adaptive optics is necessary. To satisfy this requirement, a novel concept has been taken to develop an electrostatically actuated MEMS-DM with a continuous single crystal silicon (SCS) membrane, which is targeted for insertion into NGST and Gossamer Telescopes. A bulk-micromachining approach is utilized to overcome the limitation of the surface micromachining embodied in the MUMPS process thus providing optical mirror surface quality with lower influence function and higher stroke. The comparison results of the proposed DM with current state-of-the-art technologies are summarized in Table 1. In this paper, an array of 4x4 electrostatic actuators for the MEMS-DM has been fabricated and the static deflection of an actuator has been measured.

2. THE MEMS-DM WITH A CONTINUOUS SCS MEMBRANE

Astronomical applications call for optical-quality continuous mirror surfaces. A continuous membrane has the advantage that it does not cause diffraction of the reflected beam, increasing the astronomical sensitivity for imaging and spectroscopic applications. Such membrane also ensures smooth and continuous phase variations across the mirror. Moreover, a device based upon SCS technology will result in a stress free membrane with excellent optical quality.

Table 1 Comparison of the designed MEMS-DM with current state-of-the-art technologies

Performance comparison	MEMS-DM design at JPL	Current SOA technologies			NGST Requirements
		Bulk-MEMS [5]	Surface-MEMS [8]	PMN [1]	
Stroke/**Min. actuator spacing** (μm)	0.5/**200**	A floating membrane with underlying electrodes	2/**300**	0.4/**1000**	1. optical quality mirror surface 2. 4 μm stroke with a low influence function; 3. cryogenic operation 4. surface stability of 0.1~10 nm in a second
Max. stroke/Actuator spacing (μm)	**4**/2000		**2~3** (?)	**2**/7000	
Surface stability (nm)	1* (goal)	N/A	N/A	0.1	
Influence function (%)	< 10		10	10	
Applied voltage (V)	160	200	300	100	
Issue	Complicated process steps to have a single crystal silicon mirror membrane	Influence function unacceptably high	Marginal surface quality	Room temp. device	

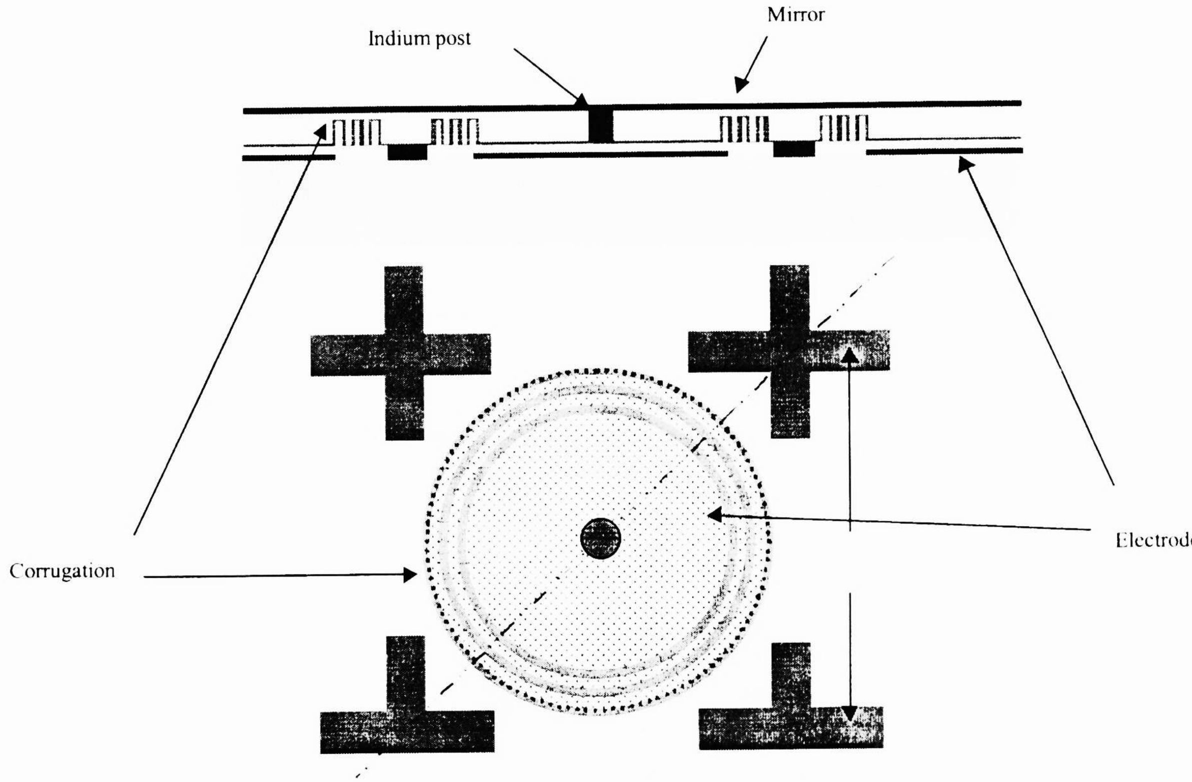


Fig. 1 The schematic view of the continuous SCS MEMS-DM backed by an array of electrostatic actuators with corrugated membranes. The mirror membrane deflects downward by the pulling force of the underlying electrostatic actuators. The device is designed to have low influence between adjacent pixels, while providing continuous optical quality mirror surface.

A key element of our approach is a MEMS-DM with a continuous SCS membrane illustrated in figure 1. The unit pixel is electrostatically actuated and has a center-to-center spacing of 200 μm. A continuous SCS mirror membrane constitutes the reflective adaptive surface, which is supported by an array of electrostatic actuators. The actuator is also a deformable membrane attached to the immobile base substrate. The corrugated actuator membrane structure is incorporated to release the residual stress caused by wafer bonding and film deposition processes. The use of both bulk- and surface-micromachining as opposed to surface-only-micromachining allows a much broader design space to optimize actuation and minimize influence function.

3. FABRICATION AND CHARACTERIZATION

A new technique for transferring wafer-level silicon membranes onto dissimilar substrates has been developed for the fabrication of the continuous SCS MEMS-DM. This technique has been used for the fabrication of the actuators with corrugated polysilicon membranes. The fabrication steps are shown in Fig. 2. A Silicon-On-Insulator (SOI) wafer acts as a carrier wafer in the Indium bonding and subsequent wet etching processes. After depositing Indium layers on both SOI and silicon wafers, the two wafers are precisely aligned and hermetically bonded. Then, the backside of SOI wafer is etched in TMAH solution. The substrate silicon is etched away, exposing a buried oxide which is subsequently removed by a HF solution. The SF_6 plasma etches the remaining silicon to release the actuator membrane structures. Fig. 3 shows the SEM photographs of a polysilicon membrane with 1 μm in thickness, which has been successfully transferred to a dissimilar silicon wafer. The membrane with underlying electrodes constitutes the 4x4 electrostatic actuators.

The WYKO RST Plus optical profiler, a commercially available instrument, is used to accurately measure the surface topography and the static deflection of actuator membranes. The images depicted in Fig. 4 show that the fabricated actuator membranes have initial upward deformation due to the residual stress in the polysilicon. The actuator membrane with more uniform surface profile is being fabricated.

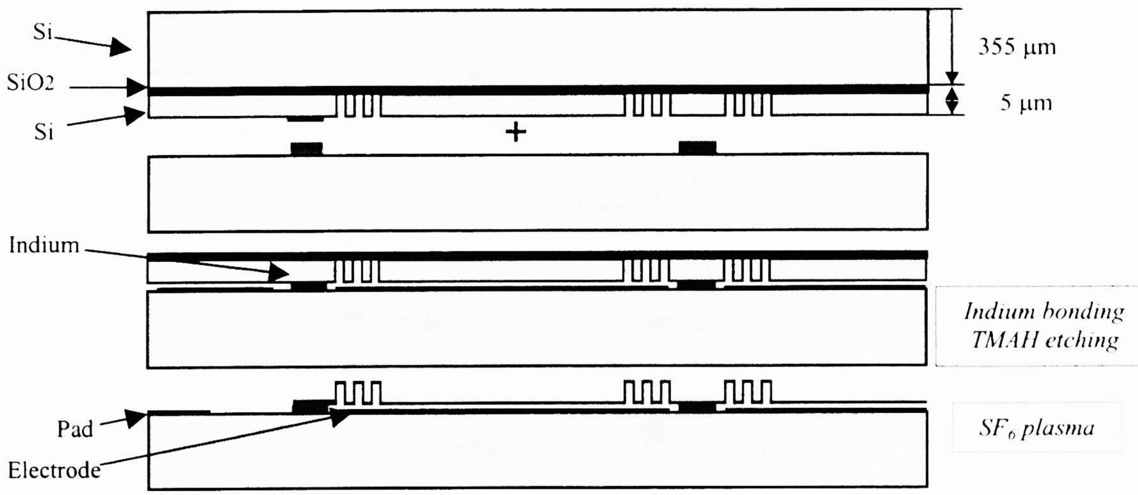
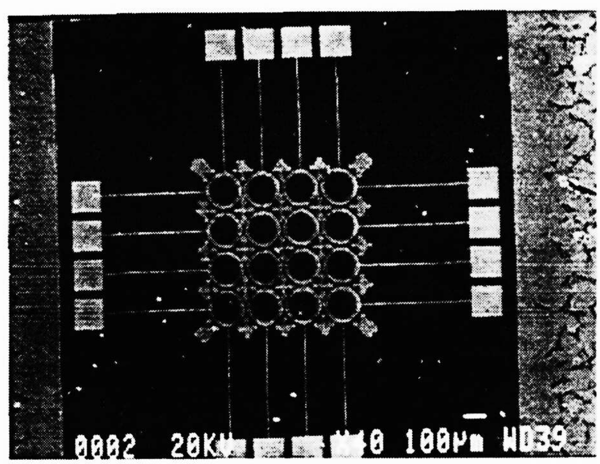
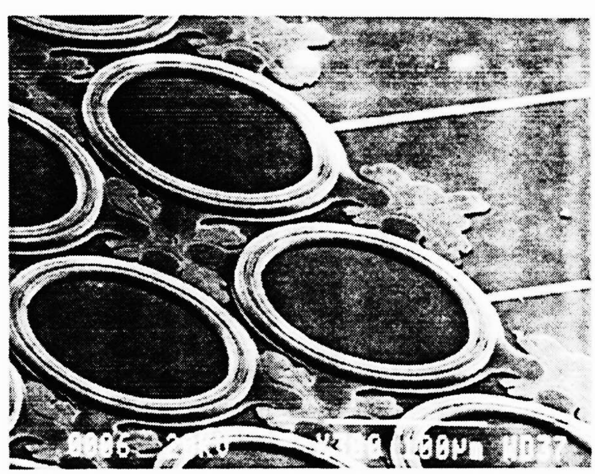


Fig. 2 The process sequence of the wafer-level silicon membrane transfer.

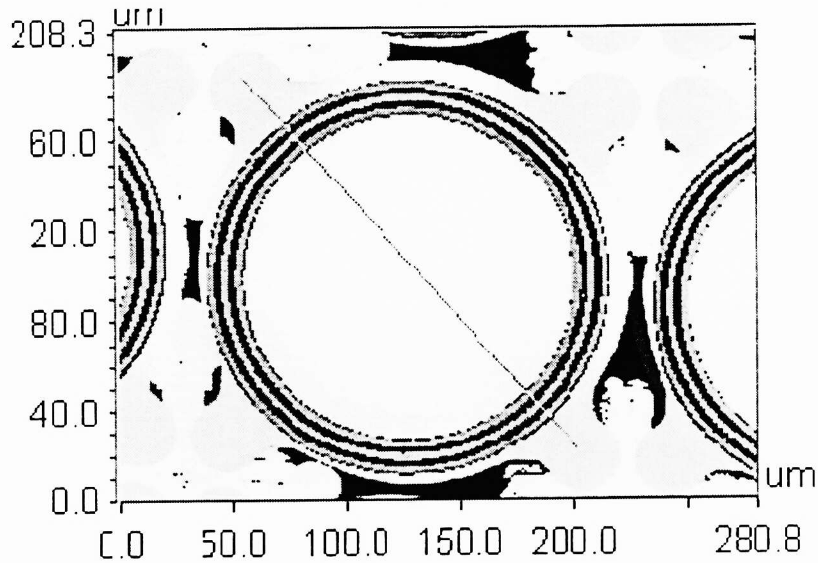


(a)

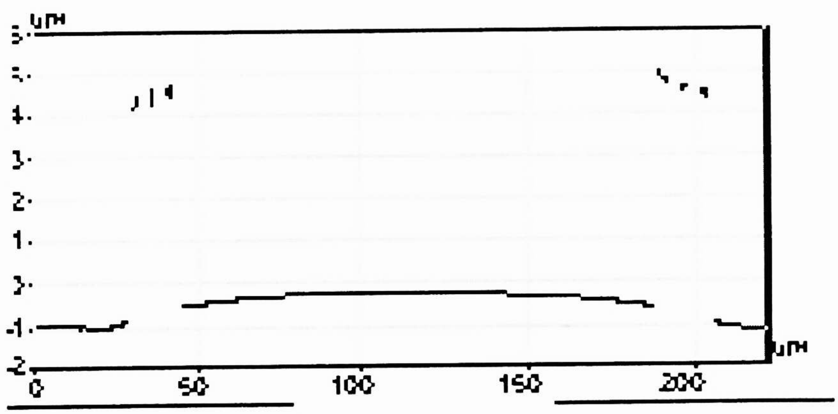


(b)

Fig. 3 The SEM photographs of the fabricated actuators with a corrugated polysilicon membrane. The device is fabricated by the membrane transfer technique utilizing the Indium bonding and subsequent dry/wet etching technologies. (a) The 4x4 actuators array (b) Enlarged view of the corrugation profile



(a)



(b)

Fig. 4 Surface profiles of the fabricated actuator array. The center flat membranes show upward deformation by the constraint due to the residual stress in the polysilicon film. This deformation can be reduced by modifying the membrane profile. (a) Surface profile of a actuator membrane (b) 2-D view of the profile of the membrane

Fig. 5 shows the deflection curve of an actuator membrane over the applied voltages. The membrane deflection is constrained by the surrounding corrugation, though the corrugation releases the residual stress in the polysilicon film. The mirror membrane transfer technology is under development to create a stress-free high quality SCS membrane mirror over the flexible actuator membranes.

4. DISCUSSION

The optical profile measurement results show that the fabricated actuator membrane has a non-uniform surface topography and the profile of each actuator varies over its position in the array. The membrane is constrained by the corrugated profile and deflection of a membrane affects the shape of adjacent pixels. A modified actuator design is under development to fabricate actuators array with a uniform membrane profile. Each pixel is mechanically and electrically isolated in the 2^{nd} generation design. The 4 μm stroke design will be incorporated to provide the enabling capability for astronomical adaptive optics (e.g. segmented space telescopes).

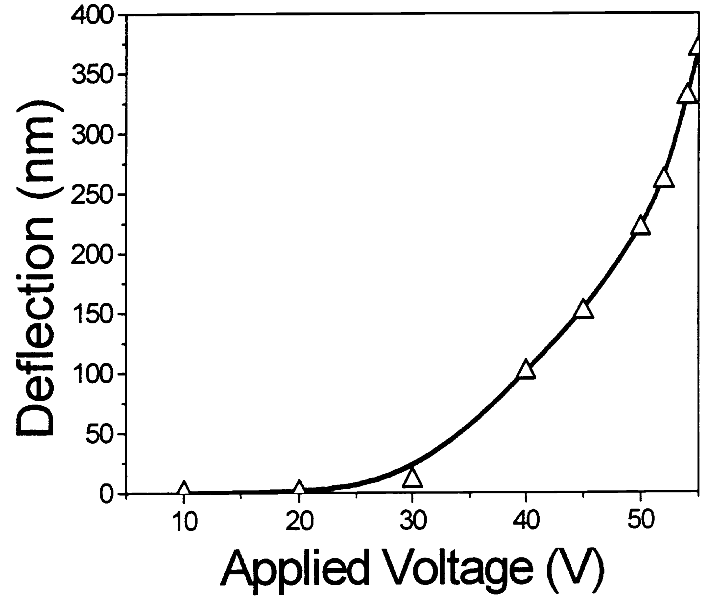


Fig. 5 Deflection of the membrane with the applied voltages.

A bulk-micromachining approach is being taken to overcome the limitations of the surface micromachining embodied in the MUMPS process thus providing greater actuator stroke, surface quality, and non-planar topography. We are exploring Indium bonding as a potential solution by forming a more compliant interface, which is an interim solution to demonstrate the device using a silicon direct bonding approach in the final design to avoid possible fracture and/or distortion due to thermal mismatch at cryogenic temperature.

Potential applications for the JPL MEMS-DM technology in addition to space telescopes include:
(a) Reduced transmitter power requirements for long distance space-to-space or space-to-ground optical communications links
(b) Very large, non-optical (e.g. A cost-effective array of high bandwidth communication stations in geosynchronous orbit.), space based apertures fabricated using Silicon telescope technology
(c) Imaging the human retina at high resolution as a biometric signature for security purposes using a very compact, portable device. Although the turbulence structure of the human eye requires only 5-10 Hz closed-loop bandwidth correction, very large numbers of actuators are required for diffraction-limited operation.

5. CONCLUSION

A new concept for building a continuous membrane SCS MEMS-DM has been proposed. The actuator membrane has been fabricated by membrane transfer technology developed at JPL. The surface profile and static deflection of actuator membranes have been measured. The transfer process of the SCS mirror membrane onto the existing actuator membrane is under development. If our approach to build a continuous membrane SCS MEMS-DM is successful, it will be a breakthrough for the development of large aperture, light-weight, space telescopes at a low cost (based on the power laws of cost-savings vs. decreasing optical quality). This technology will reduce the volume and mass of a pixel by more than two-orders-of-magnitude, which will promote the design of smaller optical systems by a factor roughly proportional to the pixel size, while delivering a high quality, compact energy efficient system. This will also allow over a 10-fold increase in light-gathering capability over NGST for astronomical capabilities at similar cost, and potentially, a 10-fold increase in theoretical resolution of down looking surveillance telescopes over the HST-class observatories operating at visible wavelengths.

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